

# The SMC X-ray transient XTE J0111.2–7317 : a Be/X-ray binary in a SNR?

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## ABSTRACT

We report observations which confirm the identity of the optical/IR counterpart to the Rossi X-ray Timing Explorer transient source XTE J0111.2–7317. The counterpart is suggested to be a B0-B2 star (luminosity class III–V) showing an IR excess and strong Balmer emission lines. The distance derived from reddening and systemic velocity measurements puts the source in the SMC. Unusually, the source exhibits an extended asymmetric H $\alpha$  structure.

**Key words:** stars: emission-line, Be - star: binaries - infrared: stars - X-rays: stars - stars: pulsars

## 1 INTRODUCTION

The Be/X-ray and supergiant binary systems represent the class of massive X-ray binaries. A survey of the literature reveals that of the 96 proposed massive X-ray binary pulsar systems, 67% of the identified systems fall within the Be/X-ray group of binaries. The orbit of the Be star and the compact object, presumably a neutron star, is generally wide and eccentric. The optical star exhibits H $\alpha$  line emission and continuum free-free emission (revealed as excess flux in the IR) from a disk of circumstellar gas. Most of the Be/X-ray sources are also very transient in the emission of X-rays.

Progress towards a better understanding of the physics of these systems depends on a multi-wavelength programme of observations. From observations of the Be star in the optical and IR, the physical conditions under which the neutron star is accreting matter can be determined. In combination with hard X-ray timing and flux observations, this yields a near complete picture of the accretion process. It is thus vital to identify the optical counterparts to these X-ray systems in order to further our understanding.

The X-ray transient XTE J0111.2–7317 was discovered by the RXTE X-ray observatory in November 1998 (Chakrabarty et al. 1998a,b) as a 31s X-ray pulsar. This detection was confirmed by observations from the BATSE telescope on the CGRO spacecraft which detected the source in the 20–50 keV band. The quick-look results provided by

**Table 1.** Journal of spectroscopic observations

Date	UTC	Wavelength Range (Å)	Dispersion (Å/pixel)
1999 Jan 9	21.15	6250-6900	0.75
1996 Jan 9	21.53	6250-6900	0.75
1996 Jan 10	20.44	3700-5400	1.5

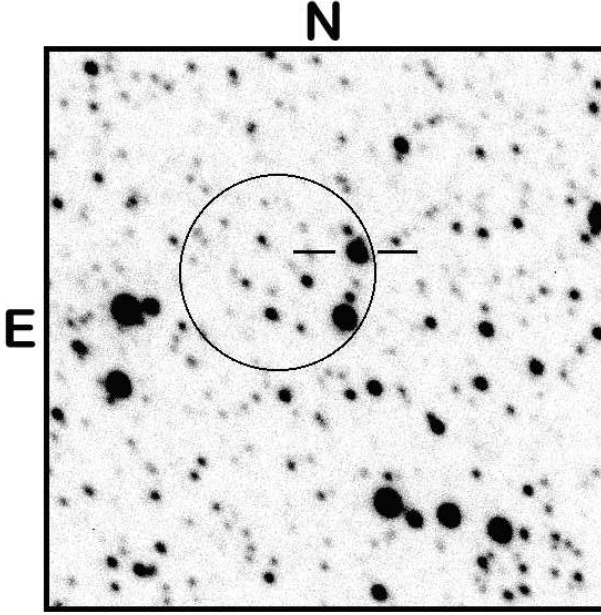
the ASM/RXTE team indicate that the X-ray source was active for the period November 1998 – January 1999. A Be star counterpart has been proposed by Israel et al. (1999) based upon optical spectroscopy.

Reported here are optical and infra-red measurements taken while the source was X-ray active which confirm the proposed identity of the counterpart to XTE J0111.2–7317. The counterpart is shown to be most consistent with a main sequence B0–B2 star. In addition, strong evidence is presented from the H $\alpha$  imaging for a surrounding nebula, possibly a SNR.

## 2 OPTICAL SPECTROSCOPY

Optical spectra were taken on 9–10 January 1999 from the SAAO 1.9m telescope. The instrument used was the grating spectrograph with the SiTe CCD detector. See Table 1 for details of the observation configurations.

The only significant lines detected were from strong



**Figure 1.** A V band image of the field containing the source XTE J0111.2-7317 (marked) and the X-ray error circle (30" radius) from the RXTE satellite. The full field of view is approximately 3 x 3 arcminutes.

H $\alpha$  and H $\beta$  emission. The equivalent widths obtained were  $-27 \pm 0.3 \text{ \AA}$  for H $\alpha$  and  $-3.8 \pm 0.2 \text{ \AA}$  for H $\beta$ . Furthermore the average redshift of the lines from their rest position was measured and this corresponded to a recessional velocity of  $165 \pm 15 \text{ km/s}$ .

The other bright star in the error circle was also checked but did not show any evidence of H $\alpha$  in emission.

### 3 OPTICAL AND IR PHOTOMETRY

Photometry of the source was obtained from South Africa using the 1.9m and the 1.0m telescopes in January 1999. The 1.9m IR data were collected using the Mk III photometer in the J and H bands. The 1.0m data were obtained using the Tek8 CCD, giving a field of approximately 3 arcminutes, and a pixel scale of 0.3" per pixel. Observations were made through standard Johnson UBVRI and Strömgren-Crawford uvby $\beta$  filters. The exact dates and filters used are specified in Table 2. The 1.0m data were reduced using IRAF and Starlink software, and the instrumental magnitudes were corrected to the standard system using E region standards.

Figure 1 shows a V band image from our observations which shows the X-ray uncertainty (30" radius error circle) and the candidate proposed by Israel et al., 1999.

The observed  $\beta$  index was determined by taking the ratio of the fluxes in the H $\beta$ -wide and the H $\beta$ -narrow filters. This was found to be 2.38 before any correction for the circumstellar emission was applied (see Section 5.1 for a further discussion of this point).

**Table 2.** Optical and IR photometry of the counterpart to XTE J0111.2-7317.

Band	8 Jan 1999	21 Jan 1999
B		$15.24 \pm 0.01$
V		$15.32 \pm 0.01$
R		$15.37 \pm 0.02$
I		$15.31 \pm 0.01$
u		$15.90 \pm 0.02$
v		$15.56 \pm 0.02$
b		$15.53 \pm 0.01$
y		$15.44 \pm 0.02$
J	$15.5 \pm 0.3$	
H	$15.1 \pm 0.2$	

### 4 H $\alpha$ IMAGING

Of particular interest with this source is the H $\alpha$  image. A 1000s exposure taken on 21 January 1999 with the 1.0m telescope revealed a clear extended structure around the Be star. Consequently a deeper 2000s image was recorded on 24 January 1999. This latter image is shown in Figure 2. Also shown in the figure is an (H $\alpha$ -R) image. This latter image was obtained by normalising the two separate images, registering the fields to sub-pixel accuracy, and then subtracting one from the other. Despite the accurate registration, variations in the PSF have caused some residual structures. Nonetheless, the result is an image which clearly shows the sources of H $\alpha$  within the field. In addition to the extended structure around XTE J0111.2-7317 and its associated Be star, one can see two other strong H $\alpha$  emitters at the eastern and southern edges of the field. These are probably also both Be stars.

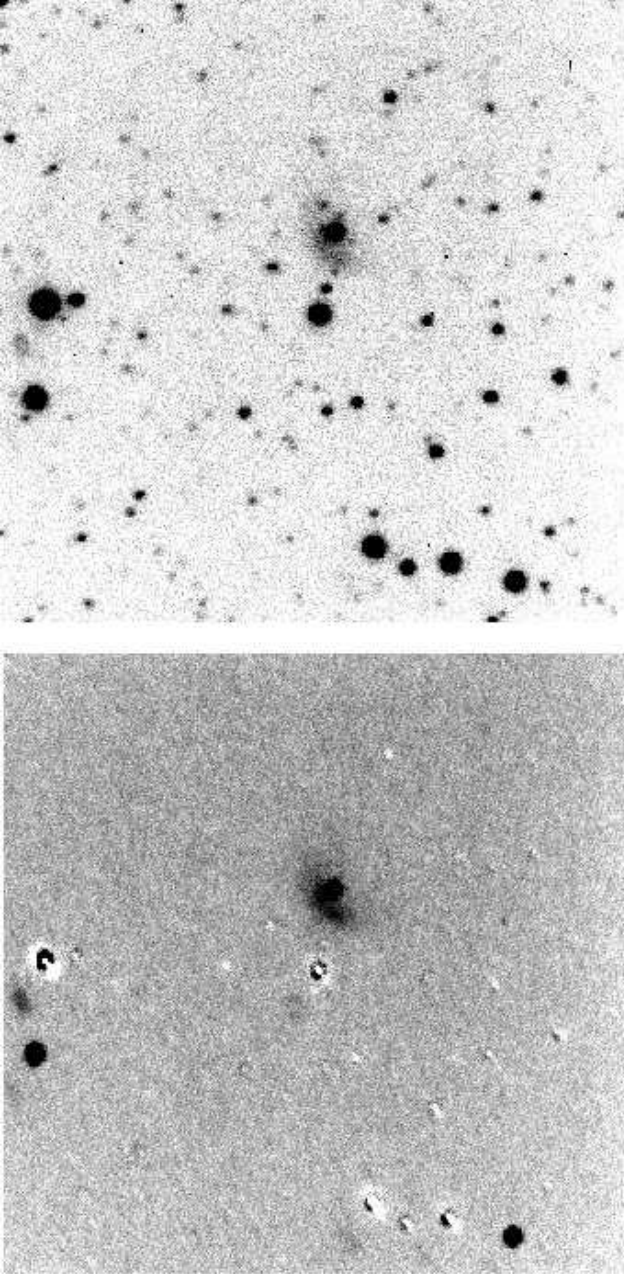
### 5 DISCUSSION

#### 5.1 Spectral Class

The equivalent width obtained for the target was  $-27 \pm 0.3 \text{ \AA}$  for H $\alpha$ . Typical equivalent widths found in Be stars are in the range 0 to  $-40 \text{ \AA}$ , while those found in supergiants stars lie below  $-4 \text{ \AA}$ . Some hypergiants (luminosity class Ia+) can reach  $-7 \text{ \AA}$  (eg Wray977, Kaper et al, 1995), but none have been reported greater than  $-10 \text{ \AA}$ . Thus the high H $\alpha$  value is a strong indicator that this source is a Be star.

The determination of the spectral type and luminosity class in a Be star is not as straightforward as in a non-emission line B-type star due to the presence of the surrounding envelope, which distorts the characteristic photospheric spectrum. In the  $(b-y)_0 - M_V$  plane Be stars appear redder than the non emission B stars, due to the additional reddening caused by the hydrogen free-bound and free-free recombination in the circumstellar envelope. In the  $c_0 - M_V$  plane the earlier Be stars present lower values than absorption-line B stars, which is caused by emission in the Balmer discontinuity, while the later Be stars deviate towards higher values, indicating absorption in the Balmer discontinuity of circumstellar origin (Fabregat et al. 1996).

Thus, in a Be star one has to correct for both circumstellar and interstellar reddening before any calibration can be used. There is no easy way to decouple these two red-



**Figure 2.** Upper panel : a deep  $H\alpha$  image of the region around the proposed counterpart to XTE J0111.2-7317. Lower panel : the same field in which the R band image has been subtracted from the  $H\alpha$  image. Both images are the same field size and orientation as that of Figure 1.

dening contributions. The iterative procedure of Fabregat & Torrejón (1998) has been used here to correct for both circumstellar and interstellar reddening.

The mean values of the interstellar and circumstellar reddening are  $E^{is}(b-y)=0.104\pm0.033$  and  $E^{cs}(b-y)=0.091\pm0.025$ , respectively. The errors reflect the accuracy of the Fabregat & Torrejón method. From the relation  $E(B-V) = 1.35E(b-y)$  (Crawford & Mandwewala 1976) we find that the *total* (i.e., interstellar plus circumstellar) extinction is  $E(B-V)=0.26\pm0.05$ .

In support of the method we point out that the derived mean interstellar excess colour  $E^{is}(B-V)=0.14\pm0.04$  is compatible with the average extinction reported for the SMC. Schwering & Israel (1991) have measured the extinction  $E(B-V)$  as lying in the range 0.07-0.09, though there is no doubt that in some localised regions in the SMC the value can be as high as 0.25.

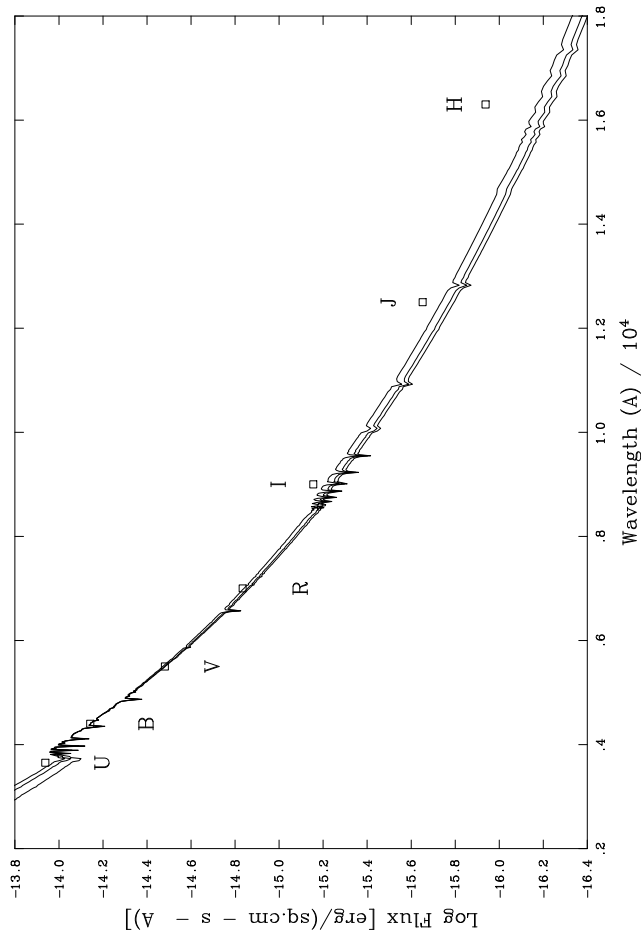
The  $c_0$  index is the primary temperature parameter for O and B type stars (Crawford 1978). Using the calibration  $\log T_{eff}=0.186c_0^2 - 0.580c_0 + 4.402$  (Reig et al. 1997) we obtain an effective temperature of  $21800\pm1200$  K. Using the calibration of Balona (1994) a virtually identical value of 22000 K is obtained. Such temperature is typical of a B1-B2 star (Zombek 1992). The same spectral class is obtained from the  $(b-y)_0$  index, which is also a temperature indicator. The derived value, -104, agrees with a B1-B2 main sequence star (Moon 1985).

Another way of determining the spectral type is by means of the Q method. The Q parameter is defined as  $Q=(U-B)-0.72(B-V)$  and it is independent of reddening. We obtain  $Q=-0.892$ , which according to Halbedel (1993) corresponds to a B1e star, in agreement with the above analysis.

The  $\beta$  index (Crawford & Mander 1966) provides a measure of luminosity class for O and B type stars. However, it is also strongly affected by circumstellar emission, with the extra complication that there is not any other independent index which can be related to the stellar luminosity. The value of  $\beta_0=2.647$  or equivalently  $M_v = -2.2 \pm 0.7$  (Balona & Shobbrook 1984) is consistent with a B2V star (Crawford 1978; Moon 1985). However, the distance implied from  $M_v$  and V is about 3 times lower than the distance to the SMC. A better approach is to make use of the knowledge of the distance modulus to the SMC. The apparent V magnitude is  $m_v=15.32\pm0.01$ . Assuming a distance modulus of  $(m_v - M_v)_0=18.8\pm0.1$  (Westerlund 1997, Table 2.4) and the derived  $E^{is}(B-V)=0.14\pm0.04$ , the absolute magnitude  $M_v$  comes out to be  $M_v = -3.8 \pm 0.2$ , closer to a B0V than to a B2III star.

If, for the sake of discussion, we assume that the correct spectral class is B1V, then the intrinsic B-V for such an object is -0.26. The photometric measurements presented here have  $B-V=-0.08\pm0.02$ , suggesting an  $E(B-V)=0.18\pm0.02$ , just about consistent with our above value from the Stromgren photometry of  $E(B-V)=0.26\pm0.05$ . If the optical/IR photometry are then dereddened by our estimate of the interstellar extinction ( $E^{is}(B-V)=0.14$ ) it is possible to compare the results with the model atmosphere expected for stars in the range B0-B2 ( $T_{eff}=30000K - 19000K$  and  $\log g=4.0$ ). These comparisons are shown in Figure 3 where the spectra have all been normalised to the B band flux. The agreement is good over the B - R range, though at longer wavelengths the usual infrared excess arising from the circumstellar disk is clearly present.

The data presented in this work include the first reported IR measurements of this system and confirm it to be an IR source similar to other Be/X-ray systems. Our data indicate an apparent colour index of  $(J-H) \approx 0.40\pm0.36$ , very similar to that seen from other SMC X-ray transients such as RX J0117.6-7330 (Coe et al. 1998).



**Figure 3.** Comparison of the observed photometric fluxes (dereddened by  $E(B-V)=0.14$ ) with the model atmosphere expected for B0 – B2 main sequence stars.

## 5.2 Extended emission

Two previous Be/X-ray binary systems have been shown by Hughes and Smith (1994) to exhibit extended  $H\alpha$  emission close to, or directly linked to the Be star. In both those objects the authors expressed the view that it was unlikely that we were observing the SNR left over from the production of the neutron star in the Be/X-ray binary system. This argument was based upon the high transverse speeds that would be needed to explain the separation of the neutron star from the deduced centre of the SNR. Such high radial velocities (approximately 100 km/s) are not seen in the optical lines, though the inclination of the motion to the line of sight would obviously affect the amount that was observable. They therefore thought it more likely that the SNR was produced from another object in the same OB association that gave rise to the Be/X-ray system. However, they did express some disquiet over finding two such systems.

In the case presented here of XTE J0111.2–7317, the association of the extended structure with the Be star seems much stronger. It is morphologically much closer than the systems of Hughes and Smith (1994) and so such high SN kick velocities are not required. One observational test that will be possible when we have better orbital data, is to search

for the high eccentricity that would inevitably be associated with a large SN kick.

An alternative explanation for the extended emission is the presence of a wind bow shock such as that detected by Kaper et al (1997) from Vela X-1. In that case the extended  $H\alpha$  emission was explained as arising from supersonic motion of the system through the interstellar medium. However, such bow shocks are more likely to occur in supergiant systems than in a Be star system. More detailed radio and  $H\alpha$  imaging may help resolve the structure of the emission.

In addition to the above 3 sources, Yokogawa et al (1999) have identified a 4th system in the SMC (AX J0105-722) which appears to be associated with the radio SNR DEM S128. So we now have 4 systems apparently associated with SNR out of the 16 probable Be/X-ray binary pulsars in the SMC.

## 5.3 Distance

The conclusion that this object is in the SMC is supported by the average velocity shift of the optical lines of  $166 \pm 15$  km/s. This compares favourably with the systemic value of  $166 \pm 3$  km/s obtained by Feast (1961) for the SMC.

## 6 CONCLUSIONS

In summary, the optical photometric measurements presented here indicate that the most likely candidate to the X-ray transient XTE J0111.2–7317 is a  $B1 \pm 1$  main sequence star. It is noteworthy that this classification falls within the narrow range of spectral types in Be/X-ray binaries, namely O9–B2. Optical spectroscopic observations in the wavelength range 4000–4800 Å are encouraged in order to refine this classification. Further studies of the extended structure will also be important in identifying its nature.

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